DEVELOPMENT OF FLIGHT TECHNOLOGY FOR FUTURE LASER-COOLED SPACE CLOCKS

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ABSTRACT

In this paper we present an overview of two experiments to fly ultra-high precision atomic clock experiments aboard the International Space Station (ISS) and perform tests of general relativity theory. In particular, we address the role played by the Jet Propulsion Laboratory (JPL) in developing the core technologies to support these and future missions. We also give an overview of the Japanese Experiment Module External Facility (JEM-EF) platform and the challenges of performing a laser cooled atomic clock experiment in this environment.

1.0 INTRODUCTION

Because of the limitations imposed by gravity on terrestrial laser cooling experiments, NASA's Fundamental Physics program has identified Laser Cooling and Atomic Physics (LCAP) as one of three disciplines (along with low-temperature and gravitational physics) which are poised to take advantage of the micro-gravity environment offered by the ISS and the Space Shuttle. Two clock experiments have been selected by NASA for flight aboard the International Space Station (ISS): the Primary Atomic Reference Clock in Space (PARCS), with principle investigators at the National Institute of Standards and Technology (NIST) and the University of Colorado; and the Rubidium Atomic Clock Experiment (RACE), with principle investigator at Yale University. In addition, 12 ground-based investigations have been funded to date on topics including atomic clocks, Bose-Einstein Condensation (BEC), Electric Dipole Moment (EDM) searches, and atom interferometry.

The Time and Frequency Sciences and Technology Group at the Jet Propulsion Laboratory plays a key role in this program, supporting LCAP missions through the design, construction and integration of instruments capable of meeting the science goals. Ground testbeds in our laboratory are used to refine our designs and aid in the development of new technologies required for the flight missions.

2.0 OVERVIEW OF THE PARCS AND RACE CLOCK EXPERIMENTS

Two atomic clock experiments will form the first generation of LCAP flight projects. Each will rely on micro-gravity for their performance and, in addition, will utilize the difference in the gravitational potential between the earth's surface and the International Space Station to perform a variety of tests of the theory of general relativity. The first of these, PARCS, has as Co-Principle Investigators Dr. Don Sullivan, and Dr. Bill Phillips of NIST, and Professor Neil Ashby of the University of Colorado. PARCS is planned to fly aboard the space station late in 2004. The other flight experiment, RACE, is led by Principle Investigator Kurt Gibble, of Yale University. This experiment differs from the PARCS experiment in that it utilizes a different atomic species (rubidium as opposed to cesium) which can result in a dramatic reduction of the collisional frequency shift, a significant accuracy limitation for cold atomic clocks. RACE is expected to fly 16 months after PARCS. We are currently targeting each of these missions to fly on the Japanese Experiment Module's External Facility (JEM-EF), an external platform aboard the International Space Station (ISS). The missions will have a duration between six months and one year.

Each of these missions is currently in its definition phase, in which their scientific goals, and the instrument requirements to meet these goals, are being developed. PARCS is scheduled to move into the design/build phase in the fall of this year, with RACE expected to begin design and build in spring of 2002.

Detailed descriptions of the two instruments have been presented elsewhere.[1,2] We present here an overview of some of the common features. Each of the two clocks will utilize a lin⊥lin optical molasses source (RACE will feature an additional collection region, to obtain larger numbers of atoms). In order to obtain high stabilities while minimizing the effect of the spin-exchange collision shift, each clock will launch multiple balls into the microwave cavity in a quasi-cw manner. This requires the instruments to utilize a system of mechanical shutters, so that those atoms within the microwave cavity are not effected from radiated light from either the source, state selection, or detection regions. The local oscillator for the PARCS mission is a space qualified hydrogen maser built by the Harvard Smithsonian Center for Astrophysics (SAO), with a short-term stability of $\sigma_y(\tau)=5\times10^{-14}\tau^{-1/2}$.[5] A local oscillator has not yet been selected for the RACE mission. Each mission will utilize GPS carrier-phase measurements both for time transfer and precise determination of the ISS orbit and velocity.

3.0 INSTRUMENT DEVELOPMENT

Instrument development and PI support for both of the current flight projects and for later LCAP flights is provided by the Time and Frequency Sciences and Technology Group of the Jet Propulsion Laboratory. Work in our ground test bed has focused initially on demonstrating the feasibility of performing laser cooling experiments in space. Here the challenges are to dramatically reduce the volume and mass requirements of a typical laser-cooling experiment, while improving the reliability and ruggedness of the apparatus. The hardware must be capable of surviving a typical space shuttle launch, and of operating autonomously for several months.

One of the most challenging technologies is the development of rugged compact laser systems, capable of producing high power single frequency laser light with the stability and frequency tunability needed to meet the demands of a laser cooling experiment. We have also demonstrated a compact laser system built within the mass and volume constraints of the PARCS mission. Our current baseline laser system for PARCS will have a single master laser (a New Focus Vortex model extended cavity diode laser) that will then be used to injection lock two higher power slave lasers. Acousto-optical modulators positioned between the master and slave laser allow one to have a very fine control of the laser frequency, while similar modulators following the slave laser allow the laser intensity to be controlled as well. We have vibration tested a variety of optical components that will be included in the PARCS laser system up to the qualification level required for a shuttle launch. These components include a Vortex master laser, and a variety of acousto-optic modulators, optical isolators and mounts. Each of the components passed the tests successfully, giving us high confidence that these devices are rugged enough to survive launch.

Another example of the unique technologies being developed at JPL is the novel non-magnetic shutter system shown in figure 1, which is required in order to utilize the launching of multiple balls of atoms without introducing light shifts. The requirements on this shutter are severe—it must be capable of performing reliably for one year in ultra-high vacuum without perturbing the micro-gravity environment, or producing any significant magnetic field, which might perturb the clock.

Figure 1. Conceptual design of non-magnetic shutter for the PARCS and RACE missions.

Other components and subsystems are also under development to provide ISS experimenters with the same capability currently available in ground-based laboratories. These include ultra-high vacuum systems, and sources of alkali atoms.
A key to minimizing the overall cost of the LCAP program is to develop experiments with as much modularity and reusability as possible. Thus the laser and optics subassembly for the PARCS experiment will also be suitable for a variety of future LCAP flights using atomic cesium. The RACE laser and optics subassembly, will have a similar design to the PARCS one, but will utilize different components in order to match the rubidium wavelength. Again, this system will be designed to be easily refurbished for future flights involving rubidium. Currently it is believed that most LCAP flights will utilize one of these atomic species.

4.0 THE JEM-EF PLATFORM

The ISS carries a number of different platforms, both internal and external, for science payloads. Of these, we have selected the Japanese Experiment Module's Exposed Facility (JEM-EF), shown in Fig. 2, as our preferred platform for both clock missions. This decision is based on a number of criteria, primarily the access to site that would be acceptable for placement of a GPS receiver for time transfer and precision orbit determination. It is also highly desirable to have both the receiver and the clock co-located. Co-location of equipment is required to determine the position of the clock relative to a ground station to within 10 cm, an amount which is less than the expected flexing of the Space Station structure over a typical orbit. In addition it is difficult to obtain a high quality rf or optical link between locations on the station that are widely separated (and in particular between locations inside and outside the station). The JEM-EF also allows both zenith and nadir pointing instruments, affording us the flexibility of adding a direct downlink frequency transfer system. Finally, a location on the JEM-EF also gives proximity to the Super-conducting Microwave Oscillator

(SUMO) instrument. A link between this highly stable oscillator and an atomic clock would dramatically enhance the science return of each instrument.[3] A link to the Atomic Clock Ensemble in Space (ACES) experiment would also be highly desirable[4], but might prove challenging if there is no direct line of sight for an optical link between the instruments (ACES is expected to be flown on either a nadir pointing Express Pallet located on the starboard side of the Space Station truss, or on the side of the Columbus orbiting facility).

Figure 3 shows a picture of a typical JEM-EF payload bus. Instruments mount into a volume 1.8× 1.0× 0.8m, and must have a mass < 500 kg. A maximum of 3000 W of power is allowed per payload (in practice this might be considerably reduced, because of the limits to the total amount of station power available). Up to 2000 W of heat can be taken away by a closed water loop. These numbers are extremely liberal compared to other ISS platforms.

A potential disadvantage of the JEM-EF platform arises from its proximity to various space station structures (in particular the solar panels), which limit the viewing of the GPS constellation, and may also produce multipathing problems--reflections of the GPS signal at the ~70dBm level (~20 dB below the expected signal amplitude) may disturb the carrier phase solution. Finally there is a powerful Ku band communications antenna on the platform that may cause interference problems.

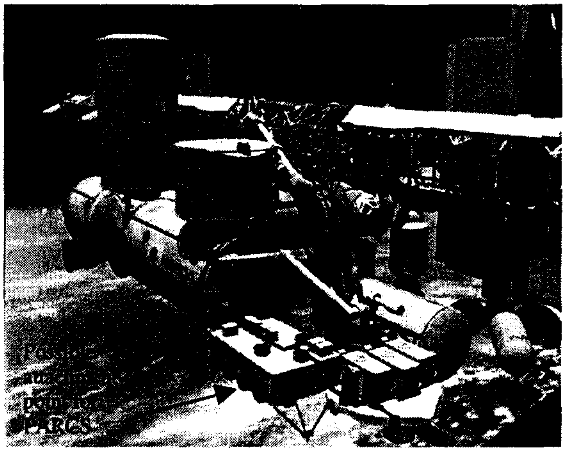

Figure 2. View of the Japanese Experimental Module's External Facility, with no payloads attached.

5.0 ACKNOWLEDGEMENTS

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6.0 REFERENCES

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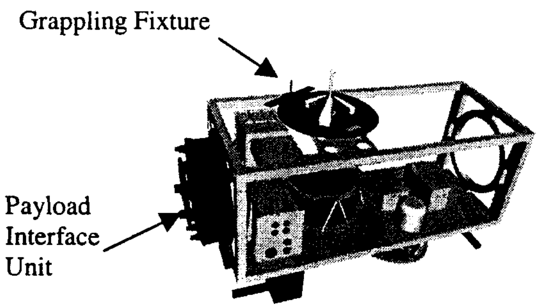

Figure 3. A sketch of the JEM-EF payload bus. (Courtesy NASA-Goddard)